Reg Environ Change (2017) 17:1479–1492
DOI 10.1007/s10113-017-1108-6

ORIGINAL ARTICLE

Human migration, climate variability, and land degradation: hotspots of socio-ecological pressure in Ethiopia

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Received: 22 October 2015 / Accepted: 10 January 2017 / Published online: 3 February 2017

Abstract In Ethiopia, human migration is known to be influenced by environmental change—and vice versa. Thus, degradation of environmental conditions can contribute to out-migration, and in-migration can cause environmental changes at the immigrants' destination. The aim of our study was to systematically identify regions in which socio-ecological pressures can arise from high population densities, migration, land degradation, and/or rainfall variability. We combined population census data at the district level with high-resolution remote sensing data regarding rainfall variability, land degradation, and land cover. We identified districts in which high population density is coupled with both a steep decline in net primary production (NPP) and large precipitation variability. The affected regions are mainly cropping regions located in the northern highlands and in the central part of the Great Rift Valley. We consider these regions to be particularly prone to environmental changes; moreover, high population density places additional stress on local natural resources. Next, we identified districts in which high in-migration is coupled with both a strong decline in NPP and low rainfall variability, proposing that land degradation in these regions is likely to have resulted from human activity rather than climatic factors. The affected regions include parts of the Awash Valley, regions surrounding Lake Tana, and the mountainous regions between Addis Ababa, Bedele, and Jima. We found these hotspots of in-migration and land degradation are dominantly grasslands regions, which have been characterized by significant cropland expansion during the period studied. Whereas exploring causal relationships between migration, environmental change, and land cover change is beyond the scope of our study, we have pinpointed regions where these processes coincide. Our findings suggest that at the regional scale, deteriorating environmental conditions can be both the cause and the effect of migration.

Keywords Migration · Climate variability · Land degradation · Hotspots · Ethiopia

The relationship between environmental change and human migration in Ethiopia: current evidence

In the tropics, environmental change and human migration are interrelated. Environmental changes—including increasing climate variability and drought—can affect human migration in several ways, particularly via their complex interrelationships with economic, social, and political factors (Foresight 2011). In turn, migration can drive environmental changes, particularly when immigrants affect the landscape (for example, deforestation for agricultural purposes (Geist and Lambin 2002) or land degradation due to an overuse of natural resources (Geist and Lambin 2004)). A relationship between environmental change and migration exists in many tropical countries,

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Editor: Nicolas Dendoncker.

Electronic supplementary material The online version of this article (doi:10.1007/s10113-017-1108-6) contains supplementary material, which is available to authorized users.

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including Ethiopia and is associated with a wide variety of conflicts (Reuveny 2007).

Although the link between declining environmental conditions and out-migration has received increasing attention in the science and policy domains, it remains poorly understood (Black et al. 2011; Foresight 2011). A small—albeit increasing—number of quantitative empirical studies have investigated the relationship between environmental change and human migration. With respect to Ethiopia, current studies typically use qualitative methods, including surveys that were designed for specific regions (Ezra 2001; Ezra and Kiros 2001; Meze-Hausken 2000; Morrissey 2013), in order to investigate how environmental conditions (e.g., drought) contribute to out-migration. Conversely, Gray and Müller (2012) combined census data regarding migration with climate data in order to draw conclusions regarding the relationship between migration and environmental conditions; this approach has also been used to study other countries in the African drylands, including Ghana (Van der Geest et al. 2010) and Burkina Faso (Henry et al. 2003). Overall, these studies emphasize that both adverse climate conditions and land degradation drive out-migration in Ethiopia. What these studies have in common is that they all focus on a select region within Ethiopia. To date, no countrywide analysis has been performed to systematically identify the regions in which environmental stress and population pressure co-occur before exploring their causal interplay in detail at the regional or local scale.

While environmental change can contribute to out-migration, in-migration can alter the environment at the immigrants' destination. Several studies explored the impact of population dynamics on land use, land cover, and natural resources in the tropics (Bonilla-Moheno et al. 2012; Carr 2004; Mena et al. 2006; Ouedraogo et al. 2010), and Pricope et al. (2013) explicitly focused on these relationships specifically in Ethiopia. However, relatively few studies have explicitly addressed the ecological consequences of in-migration. The studies performed to date accounted for in-migration processes at an aggregated level (Dessie and Christiansson 2008) were restricted to resettlement projects (Lemenih et al. 2014), or focused on the impact of in-migration on land cover (Reid et al. 2000; Tsegaye et al. 2010); however, other relevant processes such as land degradation were beyond the scope of those studies. Moreover, as with the relationship between environmental change and out-migration, the majority of studies in Ethiopia focus on select regions within Ethiopia; therefore, a nationwide picture of the spatial pattern of in-migration and land degradation—and the concurrence of these two processes—is currently lacking.

Aside from the limited number of empirical studies regarding environment-driven out-migration (on one hand) and in-migration-driven environmental change (on the other hand), none of the studies performed to date have explored both processes together. Therefore, the aim of this study was to address this issue by systematically identifying regions in Ethiopia with pressures arising from in-migration, land degradation, changes in human population, and rainfall variability. This study lies at the interface between environmental science and social science and explores the relationships between human behavior, climate variability, and land degradation in coupled socio-ecological systems. This study is the first attempt to provide a district level, countrywide assessment of biophysical and demographic dynamics from 2000 through 2009. Therefore, this study builds upon existing anecdotal evidence regarding the relationships between land degradation, climate variability, and population pressure in Ethiopia. First, we identified regions in which high population pressure coexists with both increasing land degradation and precipitation variability, thus identifying regions that potentially face out-migration due to adverse environmental conditions. Next, we identified "hotspots" of land degradation and in-migration by combining population census data with high-resolution time series of net primary production changes and precipitation variability. Lastly, we characterized in-migration hotspots and hotspots of potential out-migration according to their land cover to identify possible land cover patterns inherent to these regions.

Research design

Study area

Ethiopia is located in the East African Horn region and is characterized by vast highlands, with mountains and dissected plateaus divided by the Great Rift Valley, which runs from southwest to northeast. The highlands are surrounded by low-lying savannas and semidesert regions. Ethiopia's elevation ranges from approximately 4500 m above sea level (in the Eastern Afromontane region) to below sea level (in the Northeastern Afar Depression) (Fig. 1). Ethiopia's diverse elevation and terrain largely determines the country's distribution of climate zones, soil types, land cover, and land-use pattern, as well as its human settlements. With respect to annual climate, Ethiopia is characterized by two main wet periods: the *Belg* period with brief bouts of rainfall (March through June) and the *Meher* period with long bouts of rainfall (June through September). The *Meher* season is considered the primary rainy season; 90–95% of the nation's total cereal grains are grown during this period. The timing of these two rainy seasons differs slightly across the country, but overall, the period March through September is often

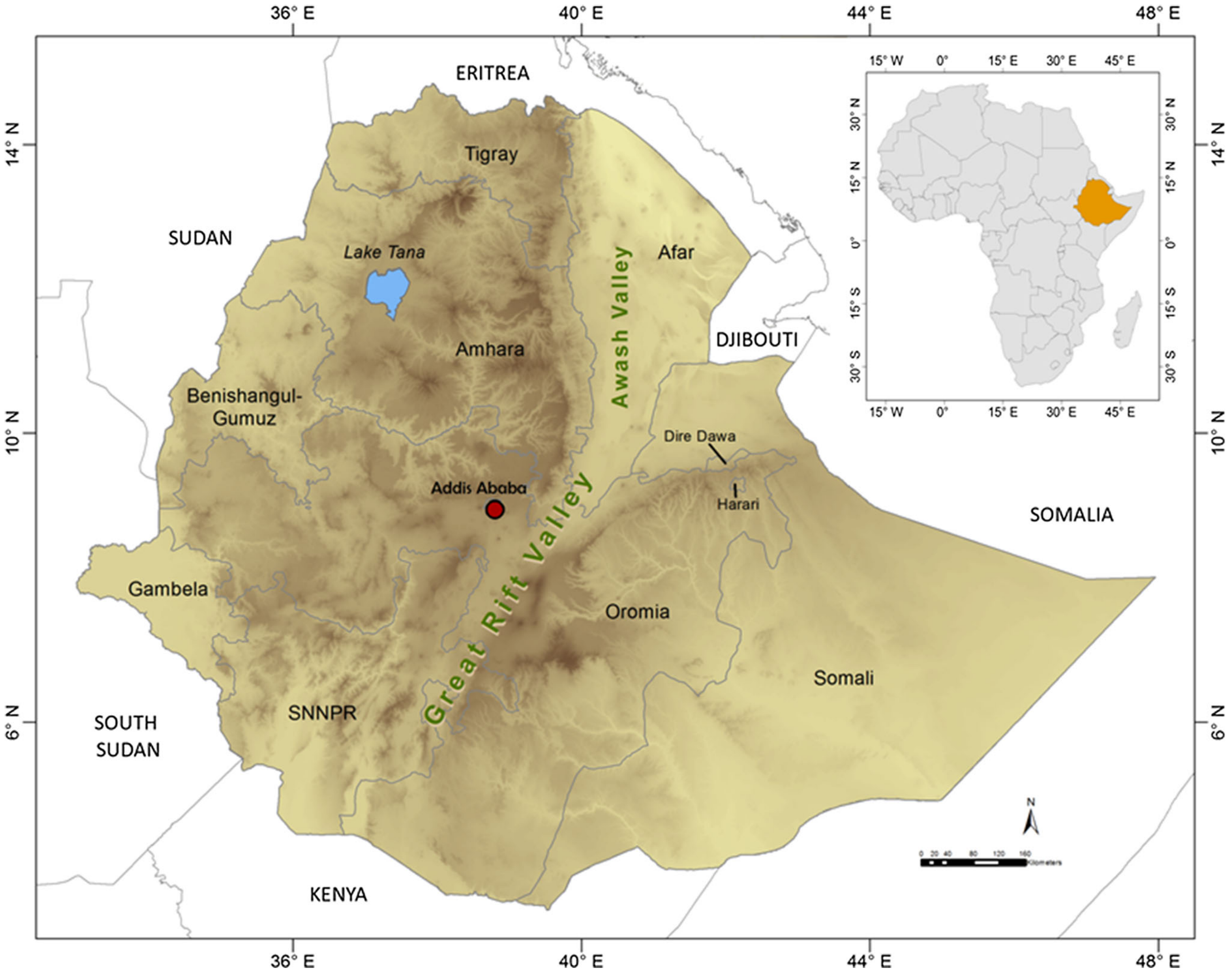


Fig. 1 Location map of Ethiopia and topographic map of the country, showing the Ethiopian administrative regions and the capital city of Addis Ababa. The darker shades of brown indicate higher elevations; elevation ranges from 200 meters below sea level to 4500 meters above sea level. The map is based on elevation data obtained from the Shuttle Radar Topography Mission (SRTM) at 250-meter resolution (Farr et al. 2007)

referred to the growing period. The annual rainfall in Ethiopia varies from less than 100 mm/year to as much as 2500 mm/year and is highly variable. This variability of the intra-annual rainfall distribution has major implications with respect to the growth of vegetation, including grasslands, savannas (including woody savannas), shrublands, and forests. For millennia, Ethiopian landscapes have also been shaped by a variety of human activities, including forest logging, land conversion for permanent croplands, and shifting cultivation and livestock production (with increasing livestock density). A common consequence of these activities is the degradation of land in croplands, rangelands, and woodlands (Gemedo et al. 2006; Meshesha et al. 2014; Solomon et al. 2007). Pressure arising from human activities is exacerbated by high population pressure; Ethiopia currently has the largest population of all landlocked countries worldwide and is the second most populous country in Africa. The majority of the population (84%) lives in Ethiopia's rural areas (CSA 2007).

Data

Demographics

We used demographics data obtained from the 2007 Ethiopian population census (CSA 2007), which provide numbers regarding the total population and number of immigrants at the district (*woreda*) level. Based on these census data, we calculated the population density in each district for the year 2007 in order to correct for the size of each district. Ethiopia contains 669 districts, all of which were included in our analysis. We used population density information to determine which regions had high population pressure. Immigrants for the year 2007 are reported as the total number of registered migrants (aggregated across all age groups, ethnic groups, and religions) that have moved to a district from outside that district. Using this information, we calculated numbers of immigrants for 2000 using census data regarding *i*) the number of immigrants who had been in the district for ≤4 years (i.e., people that immigrated between 2003 and 2007), and *ii*) the number of immigrants who had been in the district longer than 4 years but shorter than 10 years (i.e., people that immigrated between 1997 and 2003). Assuming the numbers of immigrants were equally distributed between 1997 and 2003, we calculated numbers of immigrants for the year 2000 [Eq. (1)].

$$Immigrants_{2000} = immigrants_{2007} - immigrants_{2003-2007} - immigrants_{(1997-2003)/2} \tag{1}$$

Based on these absolute numbers for 2000 and 2007, we calculated the density of immigrants (i.e., the number of immigrants per square kilometer) for the years 2000 and 2007; we then calculated the change in the density of immigrants between 2000 and 2007 (expressed as a percentage). In addition to calculating density change, we calculated the number of immigrants who moved into each district between 2000 and 2007 (expressed as a percentage of the total population in the respective district in 2007).

Net primary production (NPP)

NPP is the amount of energy that is captured by plants during photosynthesis and is accumulated as biomass. NPP is a major determinant of carbon sinks in terrestrial ecosystems (Thompson et al. 1996) and usually represents the mass of carbon captured per area per year. As such, NPP can be linked to the availability of natural resources including the supply of food, feed, and biofuel. In Sub-Saharan Africa, including Ethiopia, NPP from croplands, rangelands, and woodlands is essential for maintaining food security and for meeting energy demands; however, it is under increasing pressure due to population growth and climate change (Abdi et al. 2014). In our analysis, we used NPP data as measure of plant material available for consumption as food, fuel and feed (i.e., absolute NPP) and land degradation (i.e., NPP change). Land degradation can be defined as the long-term loss of land productivity and ecosystem functions—caused by natural and/or man-made disturbances—from which land cover can recover only with the support of land management programs (Bai et al. 2008).

We obtained MODIS (Moderate Resolution Imaging Spectroradiometer) NPP data (MOD17) for the period from 2000 through 2009 from the NASA Earth Observation System (http://www.ntsg.umt.edu). MOD17 is a simulation product based on the MOD17 algorithm, which uses information regarding land cover, the Fraction of Photosynthetically Active Radiation (FPAR) and Leaf Area Index (LAI) (MODIS MOD15 LAI/FPAR), temperature, incoming solar radiation, and vapor pressure deficit to obtain NPP (Running et al. 2004; Zhao and Running 2010). First, we used the mean annual NPP data to calculate the average NPP for the period from 2000 through 2009. In doing so, we were able to identify districts with low NPP supply that we considered to be potentially vulnerable to land degradation. Next, we obtained NPP trend information, calculated as the linear slope of 10-year annual total NPP (2000 through 2009) against years from Zhao and Running (2010) in order to identify NPP dynamics per district. Both the mean NPP and the NPP trend are measured in grams of carbon per square meter per year ($gC/m^2/year$). Unlike the demographic data, the NPP data cover an additional two years (2008 and 2009) in order to account for any lag in the response of in-migration with respect to its impact on land cover, land management, and/or land degradation. The NPP data were averaged per district to match the resolution of the population data used in this study.

Precipitation variability

For the growing period March through September, we used gridded precipitation data obtained from the Climatic Research Unit (CRU) TS (time series) 3.21 dataset with spatial resolution of 0.5° (Mitchell and Jones 2005). Specifically, we used the precipitation sums for each month in the growing period. To match the gridded NPP data, the precipitation data were rescaled and re-projected to the raster properties of the NPP data. Using the gridded monthly data, we derived monthly averages per district. Based on the aggregates per district, we calculated the mean precipitation for each year's growing season across the entire study period. Using these annual growing season averages, we calculated the standard deviation of precipitation for 2000 through 2009 in order to be consistent with the NPP data. The standard deviation was used as an indicator of precipitation variability. We included precipitation variability in our analysis for two reasons. First, previous groups (Milesi et al. 2005; Running et al. 2004) identified precipitation as the climate-related factor that most constrains NPP in countries at the Horn of Africa, including Ethiopia. Hence, in our study we used precipitation variability to distinguish between regions in which a declining NPP is likely to be a result of limiting precipitation and regions in which it is not. The second reason we included precipitation variability in our analysis is because precipitation in regions that depend on natural resources can significantly affect the livelihood of local populations, primarily through mechanisms related to the production of crops and livestock (Morton 2007; Sissoko et al. 2011). Thus, the ability to identify regions with highly variable precipitation supports the ability to pinpoint regions that have increasing stress on local livelihoods, which typically require adaptation measures, for example, migration (Adger et al. 2003; Osbah et al. 2010). Appendix of Esm 1 graphically illustrates the variability of all indicators. The respective district-level maps that were used in our study are provided in the Appendix of Esm 2. Appendix of Esm 3 provides a statistical overview of all indicators used in the presented analysis.

Land cover

We characterized the identified hotspots of both potential out-migration and in-migration according to their land cover to identify possible land cover patterns inherent to the hotspots. To achieve this, we used data from the Regional Centre for Mapping of Resources for Development (RCMRD) (http://geoportal.rcmrd.org/maps/105), which provides 30-meter resolution land cover data for 2003 and 2008 for Ethiopia. The land cover maps have been derived from Landsat 5 imagery using supervised classification. We used the land cover scheme I, which distinguishes between the six land cover classes forestland, grassland, cropland, wetland, settlement, and other land. The land cover maps were validated using randomly generated point interpretation and actual field data. According to the accuracy assessment of the land cover data, the overall classification accuracy for 2003 and 2008 is 88 percent and 87 percent, respectively (RCMRD-SEVIR Africa 2015; for details, we refer to Appendix of Esm 4). For the purpose of our study, we calculated the fractions of land cover types for entire Ethiopia and both potential out-migration regions and in-migration regions.

Data integration and analysis

First, we pinpointed the regions in which negative NPP trends and low NPP supply co-occur with high population density and high precipitation variability, thus identifying regions with high environmental and demographic pressure. We consider that out-migration as a possible response to adverse environmental conditions is more likely in these regions compared to other regions in Ethiopia. Next, we identified regions with high in-migration pressure, and we explored their concurrence with land degradation (expressed as a decline in NPP). Finally, we identified land cover patterns of both putative out-migration regions and in-migration regions in order to pinpoint possible commonalities.

Hotspots of pressure arising from the environment and humans

To identify hotspots of land degradation, climate variability, and population pressure, we used a two-step approach. First, we combined NPP trends for 2000 through 2009 with mean NPP supply for the same time period in order to identify districts with adverse NPP characteristics. To identify these districts, we split these two NPP indicators into quartiles; we then selected all districts that fall into both the lowest two quartiles of NPP trends (i.e., the quartiles with the largest NPP decline) and the lowest two quartiles of mean NPP (i.e., the quartiles with the smallest absolute NPP). Using this overlay approach, which is based on splitting the indicator values into quartiles and does not consider any weighting, we identified the districts in Ethiopia in which NPP decline is the largest and in which absolute NPP supply is below the national average. For these districts, we propose that declining NPP is particularly stressful to natural resource systems. Second, we explored the extent to which the districts identified above are characterized by both precipitation variability and population pressure. As in the first step, we split the two indicators (i.e., population density and precipitation variability) into lower and upper halves. All districts belonging to the upper halves of both indicators were overlaid to identify the districts in which above-average population density coincided with above-average precipitation variability. For all districts that fulfilled these conditions, we hypothesize that the livelihood of the local population is at risk, and migration is a possible response to that risk.

Hotspots of pressure arising from land degradation and in-migration

To identify hotspots of in-migration and land degradation, we applied a two-step approach similar to the above-mentioned approach used to identify potential out-migration regions.

First, we split the indicators NPP trends from 2000 through 2009 and precipitation variability for the same time period into quartiles and overlaid the two lower quartiles of each indicator to identify districts in which a strong decrease in NPP coincide with below-average precipitation variability. For each district that fulfills both conditions, we hypothesize that land degradation is less likely related to rainfall anomalies but rather human activities.

Second, for each land degradation hotspot identified, we explored the extent to which it is characterized by immigration. For this, we combined the immigrant density change between 2000 and 2007 and the immigrant percentage in 2007. For each district that is characterized by both an above-average immigrant percentage and above-average immigrant density change, we hypothesize that pressure on natural resources arising from in-migration is the strongest pressure among all districts. For the identified districts, we suggest that NPP decline and in-migration are potentially linked.

Results

Hotspots of pressure arising from the environment and humans

Figure 2 (upper panel) shows the pattern of combined NPP levels and NPP trends in each district in Ethiopia. In general, the central highlands are characterized by above-average NPP levels, whereas the lowest NPP values were found in the low-lying grasslands and savannas that surround the highlands. The combination of NPP levels and NPP trends shows that local NPP resources are potentially vulnerable in the northern and central parts of the highlands (i.e., along the Great Rift Valley and in the Awash Valley). In total, we identified 138 districts with both a below-average NPP level and a strong NPP decline between 2000 and 2009 (Fig. 2, lower panel).

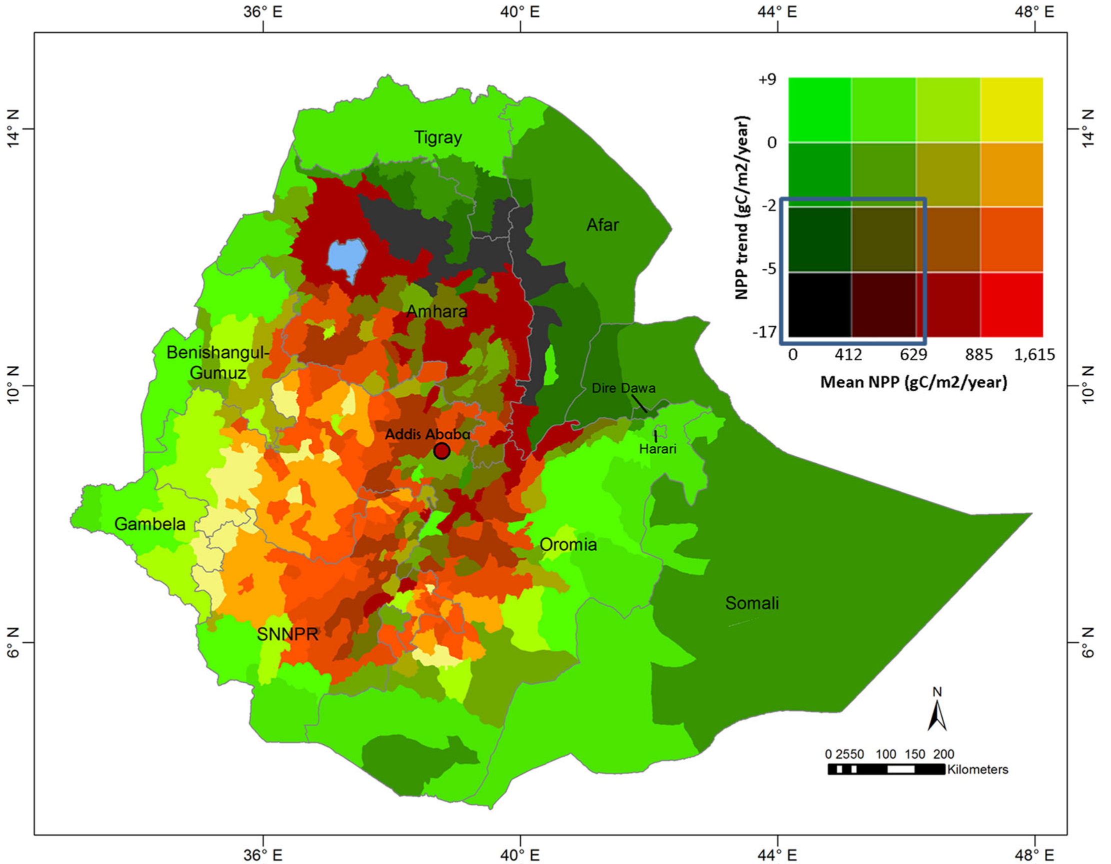
When these 138 districts are characterized according to their precipitation variability and population density, two clusters—one consisting of the northern highlands and one consisting of the low-lying areas of the Awash Valley—become apparent. The Awash Valley—as well as a few districts in the northern highlands—has a population density that is below the average of the 138 districts. Compared to the rest of the country, the precipitation variability in the Awash Valley is relatively low. We propose that socio-ecological pressure is relatively low in these regions (the black-colored districts depicted in the lower panel in Fig. 2) compared to all other districts identified as land degradation hotspot (Fig. 2). On the other hand, we identified 43 districts in which vulnerable NPP conditions coincide with both high precipitation variability and high population pressure; these regions (shown in olive-green in the lower panel in Fig. 2) are located primarily in the northern highlands, with a few districts scattered throughout the central part of the Great Rift Valley. These regions are particularly prone to environmental changes, including rainfall fluctuations and land degradation, with additional stress on local natural resources potentially originating from high population density. These findings suggest that these fragile regions are emerging hotspots of potential out-migration due to the presence of both high population density and declining environmental conditions.

Fig. 2 Upper panel: districts categorized according to their NPP ▶ characteristics. The 16 categories represent distinct combinations of NPP trend and mean NPP. In the legend, the four blue-framed blocks represent districts with the greatest NPP decline (the first and second quartiles of the NPP trend data) and the lowest NPP level (the first and second quartiles of the annual mean NPP data). Lower panel: 138 districts with low NPP supply and strong NPP decline (according to the upper panel) categorized according to precipitation variability and population density. The 43 olive-green districts are regions in which the highest pressure arising from land degradation and low NPP levels coincides with above-average precipitation variability and above-average population density. Spatial patterns of precipitation variability and population density for the entire country are provided in the appendix of ESM 2

Hotspots of pressure arising from land degradation and in-migration

The upper panel in Fig. 3 shows the degree of land degradation and precipitation variability in each district, measured as a combination of NPP change (i.e., the change in annual amount of carbon loss or gain for the period 2000–2009) and precipitation variability (i.e., the sum of the standard deviation of the annual mean precipitation during the growing season in the years 2000 through 2009). Rainfall variability was highest in the central and western highlands. In contrast, the lowest precipitation variability occurred in the low-elevation regions, particularly within Somali, Afar, Oromia, the Awash Valley, and the Southern Nations, Nationalities, and People's Region (SNNPR) (see also the Appendix of Esm 2). Figure 3 also shows that NPP had the largest declines in the Great Rift Valley, the Awash Valley, and the central parts of the highlands (for more details, we refer to the Appendix of Esm 2). In total, we identified 130 districts in which a steep decline in NPP was accompanied by precipitation variability below the national average; these regions include parts of the Awash Valley and of the Central Rift Valley, the region surrounding Lake Tana, and in the largely mountainous areas in the SNNPR region. With respect to these regions, we propose that land degradation—expressed as a decline in NPP—is less likely the result of precipitation variability but potentially linked to non-climatic factors.

In-migration—expressed as the percentage of immigrants in the total population in 2007 and the increase in immigrant density between 2000 and 2007—is a nationwide phenomenon. However, its strength varies widely across Ethiopia, and hotspots of in-migration are scattered throughout Ethiopia (see Appendix of Esm 2). In principle, the rate of in-migration is relatively low in the vast areas of the Somali region and in parts of the western highlands. In contrast, the percentage of immigrants in the total population is above the national average in the lowlands of Ethiopia (except in the vast areas of the Somali region), and it is remarkably high along the country's borders with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Tigray
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Harari
Addis Ababa
Gambela
Oromia
Somali
SNNPR
NPP trend (gC/m2/year)
+9
0
-2
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412
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885
1,615
Mean NPP (gC/m2/year)
N
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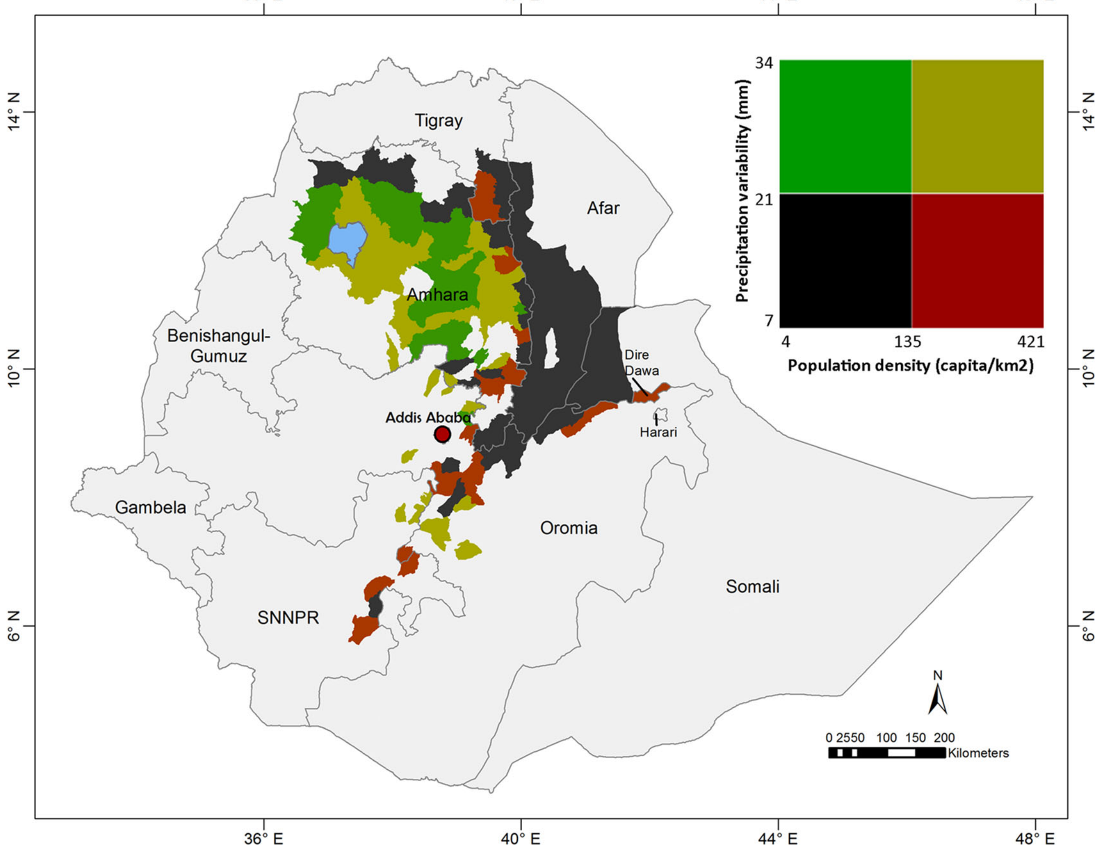
Kilometers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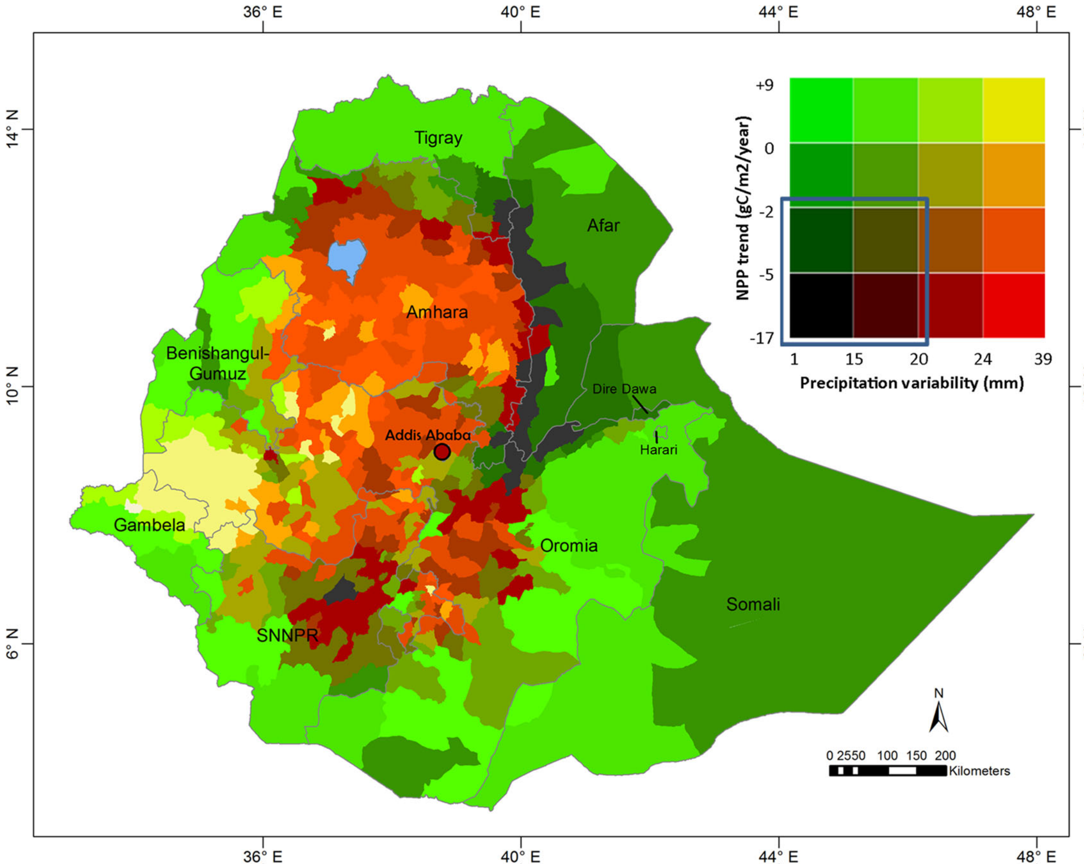
Dire Dawa
Harari
Addis Ababa
Gambela
Oromia
Somali
SNNPR
Precipitation variability (mm)
34
21
7
4
135
421
Population density (capita/km2)
N
0 25 50 100 150 200
Kilometers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NPP trend (gC/m2/year)
+9
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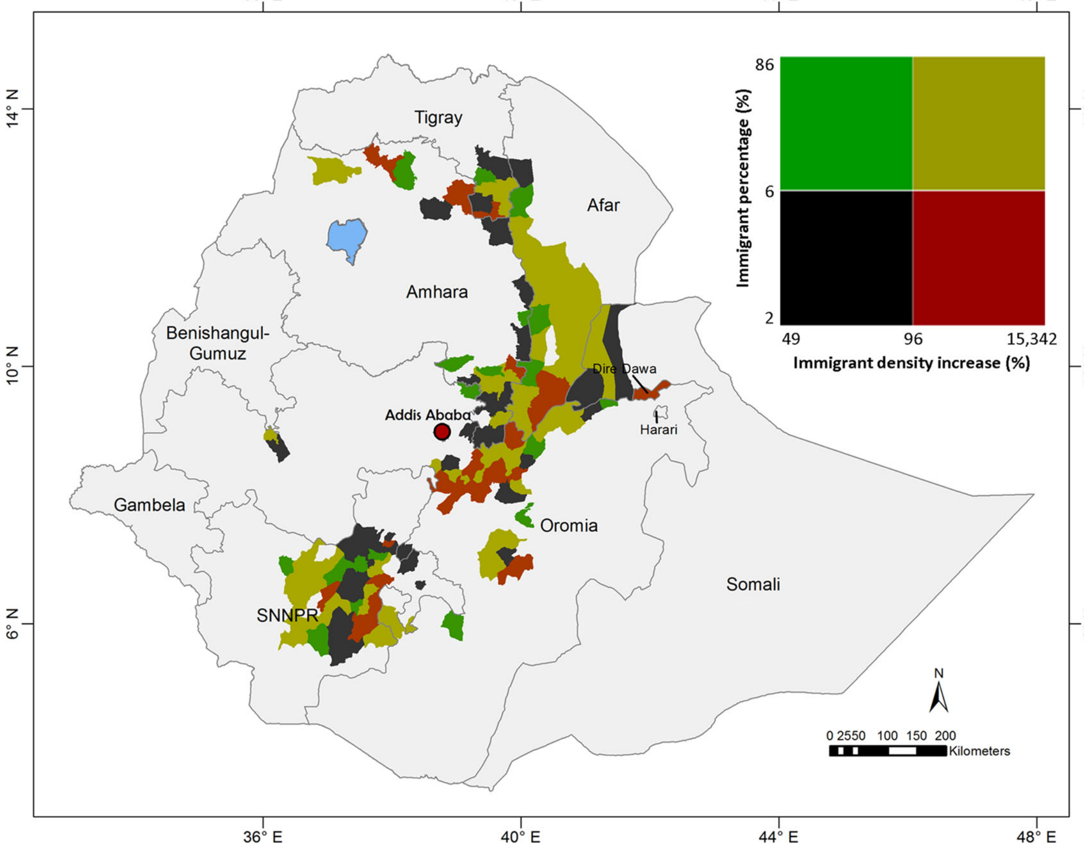
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Addis Ababa
Gambela
Oromia
Somali
SNNPR
Immigrant percentage (%)
86
6
2
49
96
15,342
Immigrant density increase (%)
N
0 25 50 100 150 200
Kilometers

◀**Fig. 3** Upper panel: districts categorized according to NPP trend and precipitation variability from 2000 through 2009. In the legend, the four *blue-framed blocks* represent districts that are below the national average in both categories. *Lower panel*: 130 districts with high land degradation and low precipitation variability (according to the *upper panel*) categorized according to their fraction of immigrants and according to the increase in immigrant density from 2000 to 2007. The 44 districts shown in olive-green are regions in which the highest pressure from in-migration coincides with the strongest decrease in NPP associated with low rainfall variability (see text). Spatial patterns of precipitation variability and NPP trends for the entire country are provided in the appendix of ESM 2

Sudan, Kenya, and—to a lesser extent—Eritrea. As shown in the lower panel in Fig. 3, the 130 identified districts have a rather patchy immigration level pattern with districts characterized by high immigration (shown in olive-green) being located next to districts with low immigration (shown in black). In total, we identified 44 districts in which in-migration levels were above the national average, NPP declined steeply, and rainfall variability was low, suggesting a possible relationship between not climate-driven land degradation and in-migration.

Figure 4 shows the hotspots of in-migration and land degradation together with the potential hotspots of out-migration due to environmental pressure; interestingly, these hotspots are generally located adjacent to each other. In terms of socio-ecological pressure, we conclude that the most strongly affected regions are clustered in a wide stretch along the Great Rift Valley and Awash Valley, as well as in the highlands in Amhara and SNNPR.

We used the land cover maps for 2003 and 2008 to characterize the identified hotspots according to their land

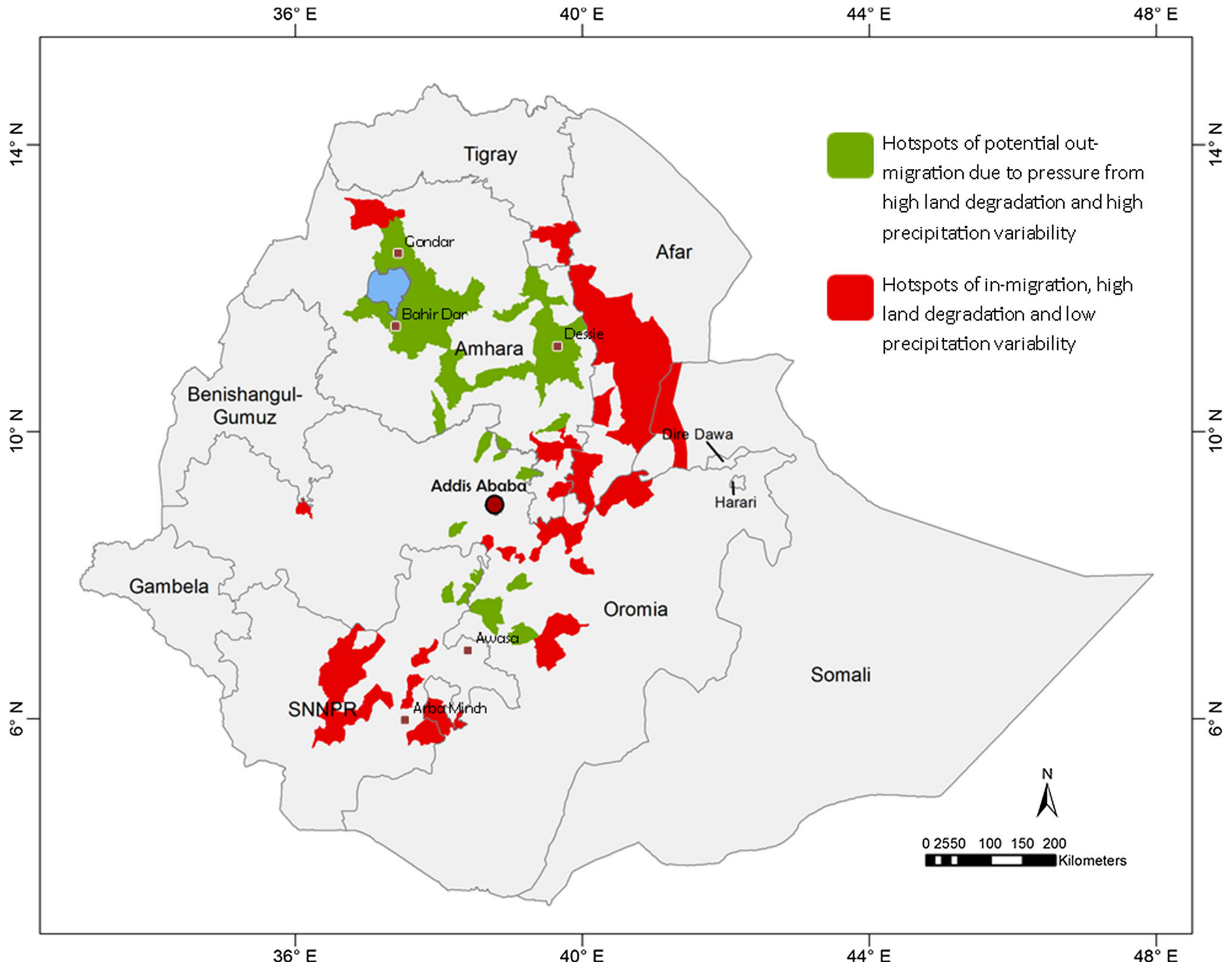

Fig. 4 Hotspots of in-migration and land degradation potentially induced by non-climatic factors (*red*) and hotspots with high population densities, high land degradation, and high variability of rainfall (*green*), thereby indicating the regions in which environmental pressure potentially contributes to out-migration. Major cities located in these hotspots and their surroundings are also shown. The hotspots are based on the 44 in-migration districts shown together with the 43 districts that are potential migration sources due to degrading environmental conditions

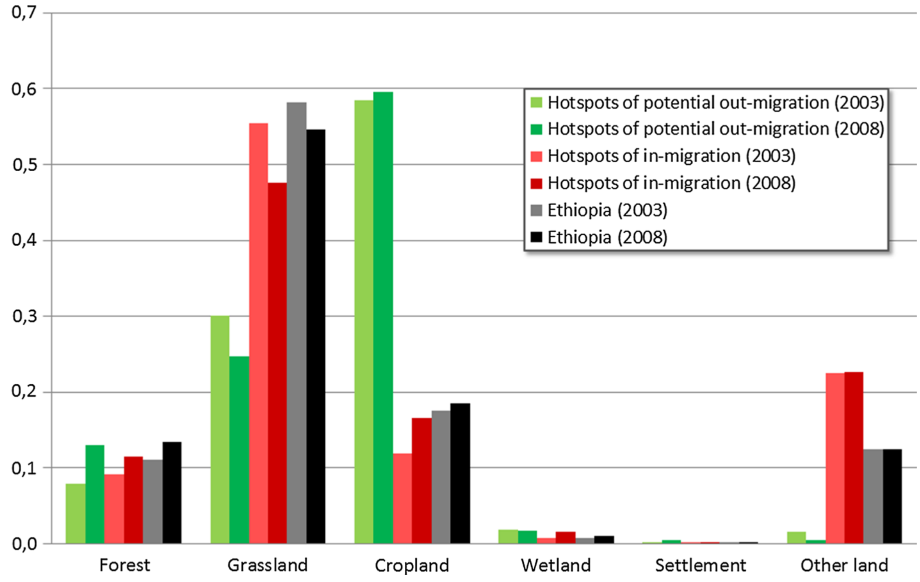

Fig. 5 Land cover composition of the hotspots. The fractions of the six land cover types are presented for the years 2003 and 2008 for hotspots of in-migration, hotspots of potential out-migration (Fig. 4) and for entire Ethiopia (including the hotspots). The spatial extent of the hotspots is identical for 2003 and 2008

cover. Figure 5 presents the fractions of land cover for both types of hotspots and for entire Ethiopia. The hotspots show strong differences in land cover composition. Whereas the potential out-migration districts are dominated by croplands, grasslands prevail in the in-migration districts. Interestingly, the in-migration districts show a 39% increase in cropland between 2003 and 2008, while the Ethiopian-wide increase was 6% in the same period (for details, see Appendix of Esm 5).

Discussion

Emerging hotspots of socio-ecological pressure

Our aim was to systematically identify hotspots of in-migration and land degradation in Ethiopia; in addition, we sought to identify hotspot regions with pressure arising from human population changes, land degradation, and rainfall variability. Our results revealed that regions that have low (and declining) NPP levels, highly variable rainfall conditions, and strong population pressure are located primarily in the northern highlands and—to a smaller extent—the Great Rift Valley. Given the population's high dependence on locally produced food, feed, and other commodities (most of which depend on natural resources), we propose that these regions are more prone to environment-driven out-migration than other regions in Ethiopia. However, the environmental factors that contribute to out-migration in rural, natural resource-dependent areas are closely interwoven with non-environmental factors (including resettlement projects, the search for education and/or additional sources of income, land shortage, political turmoil, and family-related reasons) and are usually not limited to just one direct driver of migration, as shown previously (Asfaw et al. 2010; Bantider et al. 2011; Erulkar et al. 2006; Ezra 2001; Ezra and Kiros 2001; Neumann and Hermans 2015). Therefore, suggesting that land degradation, rainfall variability, and population pressure alone can drive out-migration is likely an oversimplification; similarly, suggesting that a lack of these conditions prohibits out-migration is also likely an oversimplification. Together with previous studies that underscored the assumption that land degradation, overpopulation, and highly variable rainfall conditions (including drought) contribute to driving out-migration in Ethiopia (Ezra 2001; Meze-Hausken 2000; Reuveny 2007), our systematic assessment identified regions that are potentially prone to environment-related out-migration without explicitly considering non-environmental factors.

Interestingly, the in-migration pattern that we identified reveals a rather contrasting picture, with districts with high in-migration pressure located adjacent to districts with little in-migration pressure. This pattern is the result of a complex interplay between socioeconomic and political factors contributing to in-migration, including resettlement projects implemented by the Ethiopian government. For example, some of the districts that we identified as hotspots with both strong in-migration and high levels land degradation participated in voluntary resettlement projects in the mid-2000s (e.g., Chewaqa, Tach Armachiho, and Sodo Zuria). In these districts, the relocation of up to several thousand people has adversely affected the availability of local natural resources (for example, due to the clearing of land for agriculture), and food self-sufficiency is often not achieved (DPPC 2004). Lemenih et al. (2014) found similar results regarding the Metemma resettlement district in northwestern Ethiopia. Based on our results, the Metemma district is not a hotspot of land degradation and in-migration pressure, primarily because this region's decline in NPP was below the national average. Although our results do not exclude the possibility that land degradation coincides with in-migration pressure in this district, they illustrate that this phenomenon is stronger in other districts.

Although some spatially explicit studies explored the impact of human activity on NPP (Erb et al. 2009; Haberl et al. 2007; Imhoff et al. 2004; Ma et al. 2012), in general, humans were accounted for at an aggregate level, without distinguishing between different human activities or accounting for specific demographic processes. Gang et al. (2014) quantified the global degree of grassland degradation resulting from climate change and human activity; by comparing potential NPP with actual NPP (but without explicitly considering human activities), they identified regions with human-induced land degradation. With respect to Ethiopia, Gang et al. (2014) found human activity-induced grassland degradation along the Great Rift Valley and along the Awash Valley, consistent with our finding that these regions are hotspots of land degradation driven by human activity. In a separate study, Abdi et al. (2014) calculated the difference between NPP supply and NPP demand for the entire Sahel region by considering human requirements for food, feed, and fuel. The authors concluded that large areas of Ethiopia—particularly in the highlands, but also in the low-lying region of Somaliland—have an NPP demand that exceeds supply by at least twofold. Such an NPP deficit can be compensated—at least in principle—by NPP trade, which occurs in the form of food aid in rural Ethiopia, particularly in the highlands. Nevertheless, a large unmet NPP demand is considered to be a suitable indicator of potential land degradation.

In our study, we focused on pinpointing hotspots in which in-migration and land degradation coincide. Exploring causalities and mechanisms of the identified trends were beyond the scope of our analysis. In-migration per se does not necessarily cause land degradation; rather, land degradation is caused by a variety of inadequate land management practices by migrants and/or locals, including livestock grazing (particularly overgrazing), firewood harvesting, and the production of food and feed. These practices typically drive nutrient losses via a combination of processes, including the removal of biomass and/or erosion (Haileslassie et al. 2005). Identifying and explaining these activities in the context of migration processes was beyond the scope of our study. Nevertheless, our results indicate where population density and in-migration may put pressure on natural resources in Ethiopia, including food, feed, and fuel, particularly given that the majority of the country's rural population depend on agriculture for their livelihood (Bank 2008). The strong land cover differences identified for potential out- and in-migration hotspots (Fig. 5) provide additional indications for out-migration pressures, based on the observation that the potential out-migration hotspots are dominated by croplands under strong NPP decline and high precipitation variability. Additionally, the significant cropland expansions occurring in the in-migration hotspots between 2003 and 2008 may hint at the agricultural activities of immigrants (crops vs. livestock). Yet, land conversions in these regions are likely driven by a variety of factors, including large-scale land acquisitions for agricultural activities (Anseeuw et al. 2013). A detailed analysis of land cover change drivers was, however, beyond the scope of this study.

Limitations

Spatially and temporally detailed time series regarding land degradation have been available for the past 15 years; however, data prior to the year 2000 are limited, which hampers the ability to analyze long-term trends. Given that population census data are not available after the year 2007, the window for our analysis was restricted to less than one decade. However, migration processes can fluctuate, with periods of high migration (for example, triggered by resettlement initiatives and/or natural hazards) alternating with periods of little migration. To determine a representative migration trend, it is therefore necessary to span a sufficiently long period. Moreover, our study may have underestimated the effect of in-migration on natural resources, as the census data provide information on the number of immigrants for 2007 only. In addition, immigrants who left the region prior to 2007 could have modified the landscape but would not be included in the census data (and would therefore not be included using our approach).

We used NPP trends as a proxy for land degradation as suggested by various scholars (Bai et al. 2008; Zika and Erb 2009), which allows full consistency with the absolute NPP measure, i.e., our proxy for plant material available for consumption as food, fuel, and feed. Various studies show how alternative vegetation indices may be used as proxy for land degradation, including the normalized difference vegetation index (NDVI) (Wessels et al. 2007; Wessels et al. 2012) and rain use efficiency (RUE) (Dardel et al. 2014). However, also these indices have shortcomings (Higginbottom and Symeonakis 2014), fueling to the controversy about how to detect and interpret land degradation trends (for example, between Bai et al. (2008), Wessels (2009), and Dent et al. (2009)). Particularly for the Sahel region results of satellite-based monitoring have been intensively debated since opposite findings about land degradation were obtained (Dardel et al. 2014; Fensholt et al. 2013).

We also recognize that the NPP data used in our study integrate several types of ecosystems, including natural (savannas, forests), seminatural (managed forests, shrublands, grasslands), and man-made (agricultural systems) ecosystems. However, we suggest that changes in the NPP of natural or agricultural systems would translate into similar messages of increasing or decreasing productivity, and such signals can be used as indicators of increasing or decreasing environmental stress, respectively. A further level of detail—although beyond the scope of this study—would be to study NPP changes for various land management types; for example, although a change in crop type may produce the expected yield, it may also simultaneously lower NPP (or vice versa).

Nonlinearity in socio-ecological systems

Human responses to changing environmental conditions are highly contextual and are shaped by nonrational behavior. Therefore, socio-ecological systems are complex and are essentially characterized by nonlinear processes, including tipping points (for example, in which significant environmental changes accompanied by non-environmental factors can trigger out-migration). However, it is difficult to determine whether—and when—declining ecological conditions will trigger out-migration. Cumulative causality plays a central role; in the case of out-migration, this can be considered the threshold at which environmental impacts become so severe—and/or so frequent—that in situ adaptation options are no longer sufficient, and people eventually migrate (Bardsley and Hugo 2010). However, current conceptual models rarely account for such tipping points and are challenged by the enormous degree of nonlinear complexity arising from human–environment interactions (Meze-Hausken 2008; Neumann and Hilderink 2015). Consequently, the hotspots illustrated in Fig. 2 represent regions in which both land degradation and high population pressure more likely call for effective adaptation strategies—with migration being one possible strategy—compared to other regions in Ethiopia. However, we do not consider these districts to be hotspots of environment-induced out-migration per se.

Conclusions

In this study, we used a systematic empirical approach to identify hotspots of in-migration and potential out-migration in Ethiopia that co-occur with adverse environmental conditions, including precipitation variability and NPP decline. Our analysis revealed three key findings. First, hotspots of land degradation potentially induced by non-climatic factors, in-migration, and/or population pressure are clustered within the Ethiopian highlands and in the Awash Valley. Second, regions of potential out-migration are located adjacent to regions in which in-migration coincides with land degradation, suggesting that—at the regional scale—declining environmental conditions can serve as both the cause and the effect of migration. Third, based on the indicators used in our study, we found no coincidence of land degradation, in-migration, and/or population pressure in large parts of Ethiopia, including vast areas in the east and west. Summarizing these results, we find that hotspots of socio-ecological pressure are clustered in the Awash Valley, along the Great Rift Valley, and in the highlands in Amhara and SNNPR. Our approach enabled us to pinpoint regions in which environmental and demographic pressures occur jointly. Our method provides indications; yet, no proofs for pressures and causalities, and does thus not necessarily increase our understanding of the underlying mechanisms, which must be analyzed at higher spatial resolution using approaches that can explicitly identify and explain causal relationships between migration, environmental conditions, land cover, land management, and other putative driving factors.

Acknowledgements KNH acknowledges a VENI grant from the Netherlands Organisation for Scientific Research (NWO) and funding from the German Federal Ministry of Education and Research (BMBF) within the project MigSoKo (01UU1606).

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